

FLAVORS OF RESEARCH IN PHYSICS

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*The Heart of Matter***Rohini M. Godbole**

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Abstract

In this article I trace the development of the human understanding of the “Heart of Matter” from early concepts of “elements” (or alternatively “Panchmahabhootas”) to the current status of “quarks” and “leptons” as the fundamental constituents of matter, interacting together via exchange of the various force carrier particles called “gauge bosons” such as the photon, W/Z-boson etc. I would like to show how our understanding of the fundamental constituents of matter has gone hand in hand with our understanding of the fundamental forces in nature. I will also outline how the knowledge of particle physics at the “micro” scale of less than a Fermi (one millionth of a nanometer), enables us to offer explanations of Cosmological observations at the “macro” scale. Consequently these observations, may in turn, help us address some very fundamental questions of the Physics at the “Heart of the Matter”.

1. Concept of “elementarity” through ages.

In addressing any problem in any walk of life, the recognition of the central issue is always essential. A query of what lies at the “heart” of a given problem is of utmost importance to all of us, in dealing with various issues in everyday life. It is therefore, not surprising that, since the dawn of humanity, a major part of the scientific endeavor of the humankind has been devoted to gain an understanding as to what lies at the ‘Heart of the Matter’. The scientific knowledge and process as we know today, has developed through a desire to know how nature operates. One of the central themes in these explorations has been the wish to know whether all the matter is made up of elemental building blocks and if so how these elemental constituents are held together. In more colloquial words one might call this a quest for deciphering what the “bricks” and “mortar” of this wonderful edifice of life around us are. Funnily enough through the ages, the development of our understanding of what the fundamental constituents of matter are, has grown hand in hand along with our knowledge of the working of various fundamental processes and the fundamental forces of nature. It is this interplay that I find most fascinating.

At present particle physicists have arrived at an understanding of the basic laws of physics which govern the behaviour of the fundamental building blocks of matter, the quarks and the leptons. The interesting fact is that the same laws, *in principle*, allow us to predict the behavior of all the matter around us under all circumstances. Indeed we have come a long way since the early days of the Greek Empedocles who thought that the world was made up of the four *elements*: Earth, Water, Fire, Air. So also from the days of the early Indian sages who identified the five entities: the above four along with the “sky” as the **Panchmahabhootas**, as those whose workings need to be understood and which need to be conquered. Starting with this really “small” number of fundamental “elements” of nature, our concept of elementarity has evolved through the ages, starting from molecules, atoms, nuclei and finally ending in quarks/leptons after passing through protons/neutrons on the way, as the candidates for the basic building blocks of matter. Finally, it seems to have come home, at least temporarily, to roost in the wonderful picturesque world of “elementary particle physics”. The particle physicists, for good reason, believe that now we have perhaps peeled the last layer of the onion and the nature has revealed the ultimate constituents of matter to us. We feel that we have seen the last faceless entity at the heart of this Russian Doll. The currently accepted list of the elementary particles consists of the quarks, leptons, the force carrier particles called gauge bosons: γ , W^\pm , Z^0 , gluons along with the as yet *undiscovered* Higgs boson. It is this journey starting from the “elements” of the early Greeks/Indians to the quarks/leptons as the fundamental constituents, that I want to sketch out for you.

The subject of elementary particle physics, which is the branch of physics that deals with the ultimate layer of structure of matter, addresses the following three issues. These are:

- What are the elementary constituents of matter?
- What holds them together?
- What is the correct mathematical framework to describe how the constituents are put together to form matter, how do they interact with each other and how can one predict its behavior under different conditions?

Interesting thing is that the path to the correct answer to the first two questions at a given level of elementarity, has been indicated only by the answers to the last question at the earlier level of elementarity. A detailed account of the aspect of the elementary particle physics mentioned under point (3) above, is to be found in the article of Prof. A. Raychaudhuri, elsewhere in this volume. I would therefore not really spend much time on it, rather, I would like to chart out for you how our ideas of elementarity have changed and why we believe that quarks and leptons are indeed the ‘**fundamental**’ constituents. This means I will not discuss much about the “force carriers”. One basic point I want to make is, that in the end the essential process by which structure has been revealed has been more or less the same at all levels.

Equally interesting is another development of the past few decades, which have made us realise that this world at the smallest distance scales¹ holds clues to some of

¹ Indeed the size of an electron, if it all it is not a ‘point’, has to be less than a million, million, millionth of a meter stick

the puzzles of the Cosmos with its huge distance scales of millions of parsecs², such as why matter dominates over antimatter in the Universe or what might be the “dark matter” which does not shine but whose existence is revealed through its gravitational effects etc. The results of on going investigations in different High Energy Physics experiments at the colliders or otherwise should be able to confirm whether the explanations offered by the HEP theory to these puzzles are indeed the correct ones. Currently the most important puzzle of them all is why our Universe is accelerating? A new development in Particle physics theory extended to include gravitation, called the String theory, might have a solution for that as well! This interplay between the “micro” and the “macro” scale is one of the most amazing things and reminds me of a saying by Albert Einstein, which I freely paraphrase: ‘The most incomprehensible thing about our Universe is that it is comprehensible to human thought’.

2. Standard Model of Particle Physics

Let me begin by summarising the currently accepted picture of the fundamental constituents and interactions among them, the Standard Model of Particle Physics(SM), before I venture into a retracing of the tortuous path taken by the scientific community from the time of the Demokritos and Kanad to arrive at the SM. According to our current understanding, not only the bricks but even the mortar (the force carriers) are elementary particles. Fig. 1 shows the constituents of matter at different distance scales, beginning from atoms with a size of one tenth of a billionth meter, ending with *quarks* and *leptons*. Experiments put an upper limit on their size, which itself is a hundred million times smaller than the size of an atom and today are believed to be truly indivisible. These are considered to be the fundamental constituents of matter. Experiments at high energy accelerators, and the development of theoretical models, have together helped us arrive at this conclusion.

Quarks	Leptons
$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$ <p style="text-align: center;">× 3 colours</p>	$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$
+anti-quarks	+ anti-leptons

Table 1. *The fundamental constituents of matter.*

The quarks and leptons come in several different varieties, summarised in Table 1. The quarks are called u(p), d(own), c(harm), s(trange),t(op) and b(ottom) whereas

² One parsec is roughly 180 times the earth-sun distance, *i.e.* 27 Billion Kilometers.

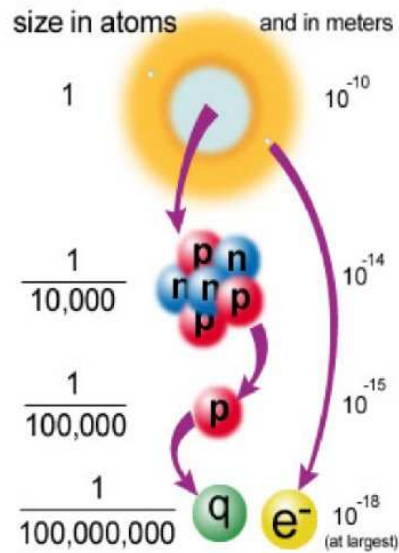


Figure 1. *Constituents of matter at different distance scales*

the leptons are the well known electron(e) along with muon(μ), tau-lepton (τ) and the corresponding neutrinos, ν_e , ν_μ and ν_τ respectively. Later we will get a glimpse of why so many varieties must be present.

As for the forces we know today that there are of four basic forces experienced by the constituents of matter:

1. Gravitational Force: The force that holds us on the earth, and gives rise to planetary motion as well as tides.
2. Electromagnetic Force: The force that holds electrons inside atoms, and that is responsible for electrostatic effects, electric currents, and magnetic poles.
3. Weak Force: The force that causes the decay of radioactive nuclei, in which a proton changes into a neutron or vice versa.
4. Strong Force : The force that binds together the quarks inside protons and neutrons, and also makes the latter stick to each other to form the atomic nucleus.

The force responsible for holding the nucleons (protons and neutrons) together in a nucleus, is derived from the Strong Force above in a similar way that the “Van der Waals” force (the force between neutral atoms holding them together in a molecule) is derived from the Coulomb interaction among the charged constituents of the otherwise

neutral atom. These forces are familiar to us to varying degrees, depending on their effects on the kind of objects that we encounter in daily life. The first two forces in the above list have been known almost since the dawn of scientific thought, while the last two are nuclear forces and were discovered only in the twentieth century. The effects of the latter two forces cannot be observed directly by the human senses, but they are just as real as the first two, since experimental equipment is certainly able to detect them. For the strong, electromagnetic and weak interaction, we have been able to show that these interactions between the constituents of matter are conveyed via the mediation of the force carriers. The interactions along with these force carriers are listed in Table 2.

Interaction	Description	Carrier Particle
Gravitation	Long-range but extremely weak attraction between all particles.	????
Electromagnetic	Long-range interaction of a quark or lepton with another quark or lepton	Photon γ
Weak	Short-range interaction that can cause different quarks and leptons to change into each other	W/Z Bosons
Strong	Short-range interaction among quarks only	Gluons g

Table 2. *Four basic forces in Nature, and the carriers for three of them.*

The lighter quarks manifest themselves only as bound states like protons, pions and kaons. The neutrinos have only weak interactions, whereas the colourless charged leptons have weak and electromagnetic interactions and the coloured quarks feel all the three interactions. The properties of all the particles, the constituent matter particles and the force carriers, have been measured to a high degree of accuracy.

Let us recall here that most elementary particles carry a “spin”, or intrinsic angular momentum. We believe this because of experiments in which particles are found to behave as if they are spinning on their own axis. This is not literally true: if it were, one should be able to change their amount of spin, or stop them from spinning, while in fact their spin angular momentum is an unchangeable property. So we must treat it as an intrinsic property of the particle. It turns out that it has to be always an integer or half-integer multiple of a basic unit called \hbar or Planck’s constant. This multiple is called the ‘spin’ of the particle. Particles of integer spin are called “bosons” and those of half-integer spin, “fermions”. All these particles have a few other intrinsic properties which have been given very imaginative and descriptive names such as strangeness, colour etc. by particle physicists and I will get back to that a little later.

The achievement of the last fifty odd years of the particle physicists as a community has been to arrive at an understanding of the working of the matter particles, the quarks and leptons, and the force carriers, the bosons and develop the mathematical framework in which this can be described. The latest in this series of developments is to develop a mathematical framework which will also might make it possible to describe workings of gravity at the same level. As already mentioned this subject does not concern us here. We will now proceed to discuss how particle physicists arrived at an understanding that these quarks and leptons are the building blocks of nature.

3. A tale of molecules, atoms and nuclei

Our concept of elementarity has undergone a change in the centuries; so has the branch of science in general and physics in particular, that has dealt with the issue. Demokritos said *'By convention there is colour, by convention sweetness, by convention bitterness, but in reality there are only atoms and space'*. In the above statement and a similar one by Kanad in Vaishyashik Sutras, there was only a conviction that all the observed properties of things around us are result of how the 'atoms' (the smallest, indivisible part of matter) are put together. This was postulated without any idea of what the atoms were and/or how they are to be put together. It was a philosophical statement. It took Sir Issac Newton, the father of Physics as we know it, to tell us how we should go about substantiating this and finding these atoms. He said in his Optics, *'Now the smallest Particles of matter may cohere by the strongest attractions and compose bigger particles of weaker virtue....There are therefore agents in nature able to make particles of Bodies stick together by very strong attractions and it is the Business of experimental Philosophy to find them out'*. Thus 'experimental Philosophy' is the earliest name one could give to this branch of science which dealt with the issue. Issac Newton was also the first one to put forward the theory of 'action at a distance' which explained the proverbial falling down of the apple, earth's going around the sun and the strange appearance of comets in the sky from time to time, in terms of *the same* interaction; viz. Gravitation. At the time of Newton and for quite some time after that, thermodynamics might have been termed as the branch of science that dealt with the structure of matter, as one could describe the behavior of three states of matter; the solid, the liquid and the gas, in terms of the laws of thermodynamics. However, already at this time a further classification was known. Chemists already knew that one can classify objects by some properties which they seem to retain, independent of the state of matter: gaseous, liquid or solid. So Chemistry, the study of these chemical "elements", could have been considered to be the branch of science dealing with this issue at that time. The regularity of patterns observed in masses, ionisation of various compounds, elements etc had led to the idea of "atoms". The ordering of these chemical elements in the Periodic Table according to their properties, put forward by Mendeleev in 1876, is one of the earliest examples of recognising order/patterns which can then be used as an experimental indication of the presence of underlying constituents. This phenomenon of an observed order/pattern/regularity in the properties of 'elemental' objects, being a smoking gun signal of a possible underlying structure, was to repeat oft in the years to follow.

The modern saga of atomicity, after the Greeks/Vedantas, begins with Dalton at the end of 18th Century. He observed that the chemical elements always combined in the

same ratio to make a given compound. He postulated therefore that the chemical elements were made of units, which he termed “atoms”³. Avagadro further found that all the gases combine in definite proportion of volume. That is the number of molecules in a given volume, at a given temperature are the same. This then led to the determination of molecular weights, molecular formulae and hence also of atomic weights. So already, by the early 19th century the Chemists knew that all the molecular weights were rough integral multiples of that of the hydrogen. So it was likely that the Hydrogen atom was the basic unit of them all! Thus the order in the atomic and molecular weights gave an indication of the possible existence of a basic building block in terms of the Hydrogen atom. Chemists kept on using the “atomic” theory without believing in the existence of the atoms till the advent of the kinetic theory of gases which gave a first principle derivation of all the observed property of gases⁴. The importance of the idea of atomicity to the world of science is very graphically expressed in the words of one of the greatest minds in physics of the 20th century, arguably next only to Einstein, Richard Feynman. He says, *‘If all the scientific knowledge in the world were to be destroyed and I can choose only one piece of understanding to be passed on to future, I would choose to pass on the message that matter is composed of atoms, ceaselessly moving and bouncing against each other’*. So at this point in the human history, one could have said that the scientists had found the “atoms” which the Greeks /Kanad had postulated and which Newton had exhorted the practitioners of “experimental Philosophy” to find.

Then in the later half of the nineteenth century came the discovery which effectively defined the shape of physical and chemical sciences for the next century: the discovery by the great Michael Faraday that the electricity too comes in multiples of a basic unit. This and the experiments J.J. Thompson performed with the Cathode Rays, helped him discover the electron, the first elementary particle, in 1897. The world of particle physics was born then. Indeed, Thompson went on to claim boldly *‘Cathode rays are matter in a new state, a state in which the subdivision of matter is carried much further than in the normal gaseous state, a state in which **all** matter, - that is matter derived from different sources such as Oxygen, Hydrogen etc. - is one and the same kind, the matter being the substance from which all chemical elements are built up.’*⁵ Thompson had thus split the “atom” by proclaiming that it was made up of electricity : positive and negative ! Existence of an electron with the mass to charge ratio as measured by Thompson was shown to explain fine details of the atomic spectral lines under the effect of a magnetic field, as calculated using an idea by Lorenz and measured by Zeeman. These experiments in 1899, helped electron make a transition from being a “mathematical entity” to being a “physical reality”. As a matter of fact the last mentioned was an important step so that people could believe in the existence of the electrons in reality,

In the above description of the discovery of the electron, we see at work, all the

³ By necessity his “atoms” were essentially what we call “molecules” today.

⁴ It is interesting to note that Einstein’s famous first work in physics in 1905 on Brownian Motion was fueled by a wish to provide ‘direct’ evidence for ‘atoms’ to the straggling nonbelievers.

⁵ To be honest this was a very bold speculation on part of Thompson, not quite justified by the results he had gotten then.

three basic processes which have helped the physicists to arrive at the current picture of the basic constituents of matter. These were

- 1) Observation by Faraday that the electricity comes in units, from patterns in ionisation,
- 2) The experiments made by Thompson which showed him that the Cathode rays behave under the action of electric and magnetic fields as though they consisted of particles with a ratio of charge to mass (the famous e/m) quite different from the Hydrogen ion,
- 3) The measurement by Zeeman of the splitting of the atomic spectral lines in a magnetic field and finding a value in agreement with that predicted using ideas by Lorenz, assuming that a particle with that value of e/m exists inside the atom.

In achieving the last it was necessary to have an understanding of how to describe mathematically the interactions of the electron (a charged particle) with electromagnetic fields. This was in place by then, thanks to Faraday and Maxwell. This is an example of the synergy mentioned in the beginning of the article, between discovering what lies at the heart of the matter and figuring out the correct mathematical framework to describe interactions among the constituents of matter.

As a matter of fact Thompson did not stop at making the bold speculation that matter was made of electrons, but gave a specific model for the Hydrogen atom called the “plum pudding model” and had worked out in detail how the very “light” electrons⁶ could make up the atom. Then came another discovery that shaped our thinking about matter again for decades to come: the famous Rutherford scattering experiment which many of us study in physics in the last years of our school these days. As a matter of fact, this is a classic example of one of the two paths to “elementarity” that has been followed by scientists in their pursuit of what lies at the heart of matter. It is complementary to the other path mentioned earlier, where one uses indications given by observing the pattern and order in properties of “elemental” objects. Very often progress in these two paths, took place side by side! I will give specific examples of this synergy in the context of Nuclear Physics and Elementary Particle Physics as we go along.

Fig. 2 depicts schematically the experiment conducted by Rutherford in which he bombarded a thin gold foil with a beam of α particles emitted by the radioactive salts. The α particles carried a positive charge twice as much as the Hydrogen ion and weighed four times as much. He then measured their angles of deflection after hitting the gold foil. In technical terms he scattered a *beam* of the α particles off the *target* of a gold foil and detected the scattered α particles in a *detector* made up of the zinc sulphide screen which produced scintillations when α particles hit it. Though it may not be very obvious at this stage, it was an attempt to “look” inside the atom using the α particles. In this case the “known” piece of theory was the good old Classical Mechanics started by Newton and Electrodynamics : the theory of how charged bodies

⁶ Electrons were found to be about 1800 times lighter than the Hydrogen atom.

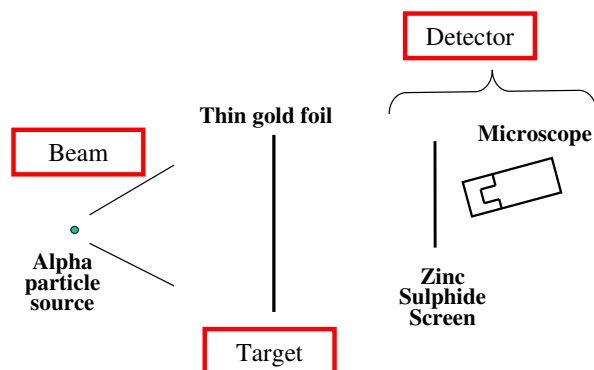


Figure 2. Schematic depiction of Rutherford's experiment.

moved under the action of electric and magnetic fields, honed to perfection by Faraday and Maxwell. Using these two one could predict the trajectory of an α particle passing through the distribution of the positive charge in the atom, which according to Thompson's Plum Pudding Model, was spread all over the atom uniformly with the e 's sticking up like plums. Recall that Thompson's experiment had revealed that the e/m ratio for the electron was much smaller than for the hydrogen ion and thus the mass of the atom was expected to be concentrated in the positive charge. Thus it was expected that all the α particles will mainly feel the positive charge and thus be deflected through very small angles. Imagine you are traversing through a big group of people uniformly spread over an area. You will have to change your "trajectory" every so often as to avoid directly colliding with another person and thus your trajectory will suffer small "deflections". Now what Rutherford discovered was something exactly opposite to the expectations of Thompson's model. Most of the α particles traversed through the foil without suffering any deflections at all, but those which did deflect did so violently. Some of them even rebounded. In Rutherford's own words, '*It was about as credible as if you had fired a fifteen inch shell at a piece of tissue paper and it came back and hit you*'.

This was a watershed of a discovery. Qualitatively it meant that all the mass and the positive charge of an atom was concentrated in a "point". So for most of the time α particles saw no charge which could repel them, i.e. most of the atom was empty space. To carry the above mentioned analogy further, consider now that you had to traverse the same road but the group of people now had gathered in a tight crowd around some object of interest in the middle of the road. If you tried to pass through the crowd you will be pushed back, but if you were initially headed in the region away from this knot of people you don't need to change your direction at all to pass through the road. This is exactly what was being observed by Rutherford with his α particles and the gold foil. Of course, what fraction of time you will be repelled back will be decided by how widely spread the "knot" of people in the centre of the road is. In more technical words, the fraction of α particles scattered at a particular angle, called the angular distribution, can give information on the spatial extent of the charge distribution. Thus they can be

used to “see” whether the positive charge in the atom had a structure or whether it was concentrated in a point. Rutherford showed that the angular distribution observed by him, agreed with the one calculated using electromagnetism and Newton’s laws of motion, assuming the positive charge to be a “point” particle. He termed this point to be the “nucleus” of an atom. Thus now the next step in revelation of the structure of matter was taken: the nucleus had arrived. The “atom” has been truly split and shown to consist of a point nucleus and a whole lot of empty space containing the electrons. At this point the fundamental constituents of matter were nuclei and electrons and they made up atoms, which in turn made up the molecules and so on.

The next decades then saw further progress in the understanding of atoms in terms of a central nucleus and electrons as well as in that of the nuclei themselves. Atomic Physics and Nuclear Physics could then have been said to be the branch of Physics dealing with the fundamental constituents of matter around us. Emergence of patterns in the properties of nuclei, such as their masses, the spin angular momenta they carried, already indicated that the nuclei, though seen to be point-like, a-la Rutherford’s measurements, perhaps had constituents. Note that while finite size of an object indicates that it has constituents, just because a particular object has a size smaller than the least count of our best measuring stick, we can not automatically conclude that the object may not have constituents. All the observed regularities in the properties of the nuclei could be explained by assuming that they were made up of protons (the hydrogen nucleus), and neutrons, neutron being an electrically neutral particle with the same mass as that of the proton. Thus the list of the “fundamental” objects at this point would have contained only a few “particles”: the photon γ whose existence was deduced from “Photoelectric Effect” by Einstein, the electron e , the proton(p) and the neutron (n). To jump a few years in this so far chronological narration, we could also include in addition the small “neutron”, i.e., the **neutrino** ν that Wolfgang Pauli, another intellectual giant, had had to reluctantly postulate to reconcile with the conservation of energy, linear momentum and angular momentum, the experimentally observed properties of the β particles observed in the decay of the radioactive nuclei.

Let us note, as an aside, that perhaps this was one of the early examples where the requirement of such conservation principles, indicative of symmetries of the fundamental processes of physics, were used to postulate a new particle. In this case the symmetry was the fact that the laws of physics are unchanged if we shift the origin of our coordinate system by a constant amount, rotate the coordinate axes and/or go to a frame of coordinates in a state of uniform relative motion. Note that this is yet another way in which some of the fundamental constituents of matter announced their presence. We will have some more examples of the same later.

4. The tale of Nucleons

But frankly this was just the tip of an iceberg. The heady developments of the early part of the 20th century on the theoretical fronts, some of which were arrived at in an attempt to describe mathematically how the nuclei and the e ’s are held together in atoms and some which sprang from the genius of one mind (that of Albert Einstein), changed the way we thought about mechanics, space and time. Till then our ideas about these were solidly grounded in the laws laid down by Newton and Galileo. A

quantum world in which time was no longer absolute was born. This is not the place to sketch out the developments of these desperately exciting times for physics which saw the emergence of Quantum Mechanics and the Theory of Relativity. We will, however, make use of one very important concept of these times, that of the wave-particle duality to take further this story of the hunt for the constituents of matter.

The question of whether a beam of light was made of corpuscles as Newton called them or whether it was a wave, was a topic of very hot discussions and dissensions on the two sides of the English Channel. The issue was decided in favor of Huygens and the wave description of light by the late 19th century. However, Einstein's explanation of the Photo-Electric effect proved conclusively that light can be seen as made up of quanta of energies. Thus by the early twentieth century the dual nature of light: as a wave as well as a particle, was an established fact. De Broglie hypothesized extension of this dual existence to all the other particles such as the electron, postulating that associated with a particle of momentum p , there is a characteristic wavelength

$$\lambda = \frac{h}{2\pi p}, \quad (1)$$

where h is Planck's constant given by 6.6256×10^{-34} joule-sec. At distance scales much larger than λ we see particle behavior and at distance scales comparable or smaller than λ the experiments will notice evidence of wave like behavior. This was indeed verified in a famous experiment by J.J. Thompson's son G. J. Thompson.

The above has a very interesting implication for the search of what lies at the heart of matter. I mentioned two ways of doing this search, that have been used historically. The first being the use of patterns/regularities to learn about possible constituents and second being scattering experiments of Rutherford. However, so far I made no mention of the much more rudimentary ways such as

- 1) breaking the system into its constituents by supplying enough energy: electric dissociation of molecules, photoelectric effect being a few examples
- 2) using microscopes with better and better resolving power. This is what was done with biological systems helping us to arrive at the cellular theory of organisms.

In fact, the experiments of the type performed by Rutherford are but a logical extension of this "visual" process mentioned in (2) above, just with a "microscope" of higher resolving power. To understand this let us recall that if we want to decrease the minimum distance between two points up to which they can be told apart, we need to use light of shorter and shorter wavelength. The phenomenon of diffraction, or bending of light around obstacles, is used to measure shorter and shorter distance scales and the limiting value is then the wavelength of the radiation used. The wavelength of visible light is several thousand Angstroms (one Angstrom is 100 millionth of a cm.). Using X-rays, which have a wavelength of a few Angstroms, we can measure distance scales of the order of a few Angstroms such as distance between atoms in a molecule etc. Note however, that this "seeing" is no longer strictly visual. The above wave-particle duality means that we can probe shorter and shorter wavelengths by replacing light with beams of accelerated particles. The higher the energy (and hence the momentum)

the shorter is the distance which we can probe. This thus is the genesis of electron microscopy.

Again, let me make a small digression and once again jump ahead a few decades. Electron Microscopy has proved a very useful tool indeed once we learned how to accelerate electrons to high energies. It has now been more than 50 years since the first image of an Atom that was taken with a Field Ion Microscope. In 1956, E. Mueller (an Indian physicist Dr. Bahadur was crucially involved in this exercise) presented the image of a tungsten tip showing individual atoms. This is shown in the Fig. 3. Sure

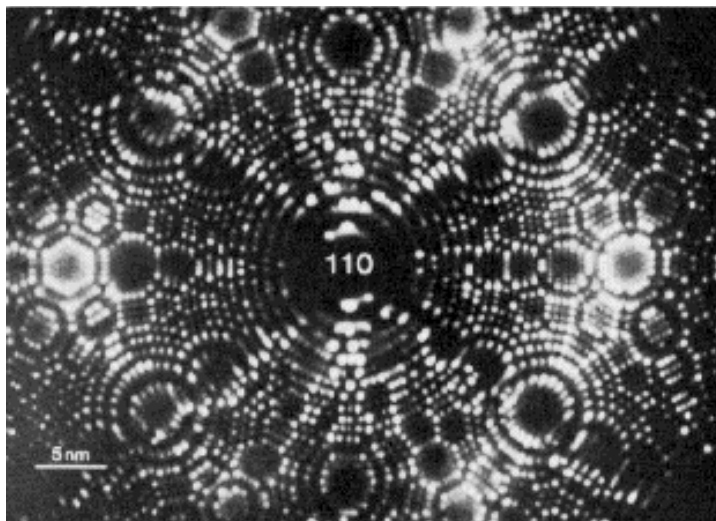


Figure 3. *Image of an atom.*

enough, by 1956 we knew atoms existed, we knew what their sizes were and so on, without ever having “sighted” the atom itself. Still this achievement was a milestone in itself as it provided the direct image of the atom and also because this marks the end of “visual” sighting of constituents of matter.

Let us get back to Rutherford and his scattering experiment. In his experiment, he was using a beam of α particles which were being emitted by the radioactive nuclei. These had revealed that the atom was not “indivisible” and consisted of a “point” nucleus and electrons around it. However, further studies in Nuclear Physics had revealed that the nuclei themselves must be made up of protons and neutrons, bound together by an attractive force. If they were indeed made up of constituents why is it that Rutherford’s experiment “saw” them as a “point”? We can answer this question by looking at the energies of the α particles used and their “resolving” power. These had energies of the order of MeV and hence the corresponding wavelength given by Eq. 1 was about one tenth of a billionth of a cm. or about a 100^{th} of an Angstrom. Thus it could resolve an object as not being a point, only if it was bigger than this distance. So Rutherford’s experiment simply meant that the nuclei, if they had a size, were smaller than this. On the other hand, since this wavelength is much smaller than an Angstrom,

which is roughly the size of (say) Hydrogen atom, this beam was capable of revealing that the atom was not a point particle, but had a distribution where the positive charge was concentrated in a very small region of the atom.

You see that we can thus use the high energy particle beams as a meter stick to measure the size of an object, by scattering the beam off the object. The De-Broglie wavelength defined by Eq. 1 gives the limit of the length scale which such scattering can probe. These high energy scattering experiments thus are, but an extension of the process of trying to put an object under microscope to determine its structure and seeing its constituents. Of course, the information is indirect and it is necessary to know the laws that govern the interaction between the “probe” and the “target” to be able to convert the observed results into an information on the “size” of the object. Thus a knowledge of the laws of dynamics at level “ n ” is necessary to probe the structure at level “ $n + 1$ ”. This point can not be overemphasized. Since one needs beams of higher and higher energies to probe smaller and smaller distance scales for existence of structure and/or constituents, the subject of ‘elementary particle physics’ is sometimes also called the subject of ‘high energy physics’. The tools we use to measure sizes of objects changes with the size that they have! This fact is illustrated in Fig. 4.

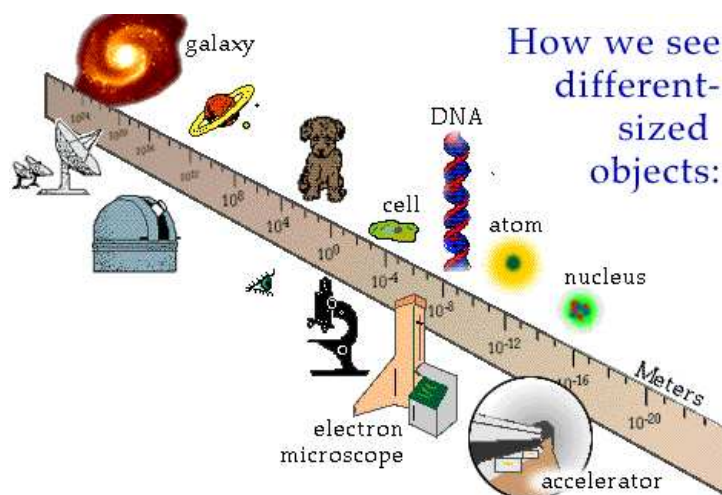


Figure 4. Tools for ‘seeing’ the objects and measuring their sizes.

Unveiling the finite size of the nucleus

The discussion so far about the processes which have unveiled the structure of matter tells us that this search proceeds essentially through three steps:

1. Seek the regularities/patterns in properties such as masses, spins etc. Very often these reflect *possible* existence of a more basic fundamental units which makes the whole: an example would be atomic theory.

2. Measure the “size” of the constituents, which at the level of atomic distances and smaller, is simply doing scattering experiments using beams of higher energy particles to get probes of shorter and shorter wavelengths: example at the atomic level of this is Rutherford’s experiment
3. A parallel and necessary step is also the development of a theory of the dynamics that holds these units together. See if the observed properties of the composites agree with the predictions of the theory: again at the atomic level the constituents revealed are nuclei and electrons, the subject dealing with the dynamics is Atomic Physics.

Discussions of the earlier sections show that at the next level, in case of nuclei, the first step of indirectly inferring existence of the constituents of nuclei, had happened in the study of Nuclear Physics. The next question was two fold: can one measure the size of the nucleus and can then one “see” the constituents in the scattering experiments. Hence one had to devise an analog of Rutherford’s scattering experiment, but one capable of “resolving” the nucleus beyond the limit of a hundredth of an Angstrom that Rutherford’s experiments could put on its size. Clearly Rutherford knew the importance of higher energies already when he said ‘*It has been long been my ambition to have available a copious supply of atoms and electrons which will have energies transcending those of the α, β particles.*’ This became possible with the advent of particle accelerators. Fig. 5 shows actually how such scattering experiments were per-

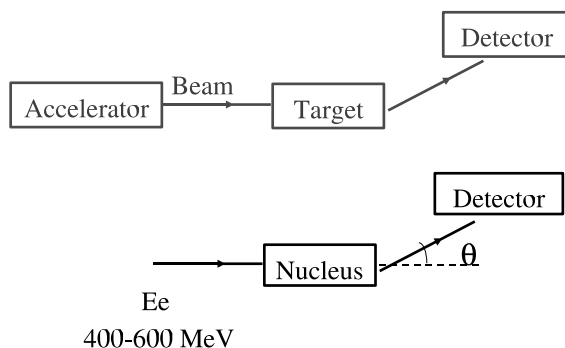


Figure 5. Nuclear/proton analog of Rutherford experiment

formed at the Stanford Linear Accelerator Centre which began by probing how big the nuclei were. In the now famous experiments by Hofstadter, electrons accelerated to energies of 400–600 million electron volts were scattered from nuclear targets. Note the similarity of the beam-target-detector arrangement with the Rutherford case. The wavelength of these electrons, λ_e , was about a 1000-10,000 times smaller than that of the α particles used by Rutherford. Again, all that the experimentalists did was to count the number of electrons scattered at an angle θ as shown in the figure and compared it with the number expected for a point-like nucleus. With the arguments made above, it is clear that this ratio will be close to 1 as long as $\lambda_e \gg R_{nucleus}$ and will

start differing from 1 as soon as the $\lambda_e \sim R_{nucleus}$. Here the nucleus is assumed to be a sphere with radius $R_{nucleus}$. Indeed, it is possible to study this ratio as a function of scattering angle θ and determine how nuclear charge is distributed in space. These experiments indicated that nuclei were about 10,000 – 100,000 times smaller than atoms. Mind you these experiments only proved that the nucleus has an extension in space, but could tell nothing whether it had any constituents. Of course since the existence of neutrons/protons, called collectively a nucleon, was already inferred from studies in Nuclear Physics, the fact that the p is not point-like did not come as a big surprise. The results of the earlier scattering experiments which had not seen any indication of the presence of nucleons inside the nucleus, could be interpreted by saying that wavelength λ_e was still much bigger than the separation between the nucleons within the nucleus and hence it could not be resolved. So at the end of this round of experiments, in 1960 or thereabouts (Hofstadter was awarded Nobel Prize in Physics for these experiments in 1961),

- 1 The fundamental constituents of matter would have been n, p, γ, e and the neutrino- ν whose existence was postulated by Pauli and confirmed in experiments in Nuclear Physics as well as their anti-particles⁷,
- 2 The elemental block of the earlier atomic level, the nuclei, were shown to have finite size and the sizes were measured by the scattering experiments,
- 3 Nuclear Physics as a discipline had been able to give a good account of all the observed nuclear properties by looking at nuclei as composites of the nucleons. The dynamics of interaction between the nucleons was developed and studied by Nuclear Physicists.

The similarity of this description with the corresponding one presented above for the atomic case can hardly be missed.

5. The last layer?

However, for various reasons none of the physicists around that time would have agreed with the above list of particles as the list of the fundamental constituents of matter. The first and the foremost reason for this, was the observation of a very large number of particles similar to n, p , but somewhat heavier than them in the Cosmic Ray experiments. These experiments studied interactions of very high energy Cosmic radiation impinging on the atmosphere, producing large number of particles. The observation created a suspicion that may be p, n are not fundamental after all. Another important indication that p/n are not point-like and are a charge/mass distribution, came from the observation that the neutral neutron had a magnetic moment. According to Dirac's equation, mentioned already in the context of anti-particle prediction, the neutral n should have had no magnetic moment at all. Even more interesting was the

⁷ Dirac's demand that the laws of Quantum Mechanics should look the same for all observers who are in state of uniform relative motion had predicted existence of an anti-particle for every particle, which would have the same mass, spin but opposite charge. The discovery of an anti-proton and existence of positrons had confirmed this prediction.

observation by Gell-Mann and Zweig that the pattern and the regularity that was exhibited in the properties of these supposedly elementary particles, could be explained by postulating that they were made up of a smaller number of more fundamental particles called quarks. However, no one had till then been able to break up the protons and neutrons into quarks, as had been possible in case of nuclei in nuclear reactions and/or decays. So people suspected that quarks were not “real” entities, but some kind of mathematical abstraction. Worse, quarks were required to possess fractional electric charges (one-third or two-third the charge of an electron), something that should have been noticed if quarks could travel around by themselves. Hence many people regarded quarks as abstract entities, and the quark model as “just mathematics”, not unlike the Chemists of the 19th Century who used Dalton’s atoms as a mathematical entity without believing in them.

According to the quark hypothesis, all the particles which experience strong interactions are made up of quarks: a proton is a bound state of two “*u*-quarks” and one “*d*-quark” and so on. The names *u* and *d* stand for “up” and “down”, but just like colour, these are abstract concepts and could easily be given any other names. Indeed, the attribute of being “up” or “down” is called “flavour”.

To account for the particles then known, one required only three different flavours of quarks: *u*(p), *d*(own) and *s*(trange). A number of different high energy experiments gave results consistent with the quark hypothesis. With the advent of higher energies and the discovery of new particles, these three flavours proved insufficient for the quark hypothesis to work. So three more flavours were added: *c*(harm), *b*(eauty) and *t*(op). This (almost) accounts for the quarks mentioned in Table 1.

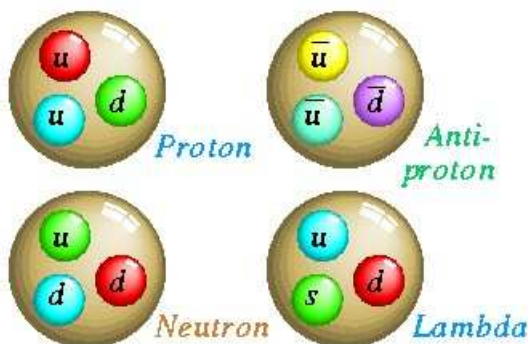


Figure 6. How quarks and anti quarks of different types make up the strongly interacting particles.

Today we believe that there exist precisely these six flavours of quarks. Their presence is strongly, though indirectly, confirmed by experiments, and is also required for consistency of the corresponding theory, the Standard Model. Fig. 6 shows the composition of some of the known strongly interacting particles in terms of different

quarks and (anti)quarks.

In 1965, soon after the original quark postulate, Greenberg, Han and Nambu proposed that each flavour of quark comes in three different species, differing only in an additional attribute which they called “colour”. They were led to this hypothesis by formal considerations. Pauli’s Exclusion Principle tells us that the wave function of a collection of identical fermions must be antisymmetric under the exchange of any two. Alternatively you may know this as a statement that no electrons with the same energy and spin can be in the same position. However, the existence of a particle called Δ^{++} posed a paradox for this principle. The paradox is straightforward to explain using ideas of quantum mechanics.

The electric charge of Δ^{++} is 2 in units of electron charge, and its spin is $\frac{3}{2}$ in units of \hbar . In terms of the quark model, Δ^{++} must consist of three u quarks. For it to have a spin $\frac{3}{2}$, the spins of the three identical quarks (each of spin $\frac{1}{2}$) have to be all aligned. Thus all the quarks would be able to occupy the same position with the same spin orientation. More technically, this says that the net wave function for Δ^{++} is *symmetric* under the exchange of any two u quarks. That would contradict the exclusion principle, a fundamental tenet of quantum mechanics. Thus the quark model, as understood at the time, had to be wrong, or incomplete.

To resolve the paradox, Greenberg, Han and Nambu were led to introduce an additional attribute, which they called “colour”, taking three different values (for example red, yellow and blue), solely so that the wave function could be made antisymmetric under an exchange of colour labels. In particular, the Δ^{++} would contain not three identical u quarks, but rather, one u quark of each colour. Then it would not be a problem to make the wave function antisymmetric and save the exclusion principle.

A large number of measurements, such as the rate of decay of a neutral pion into a pair of photons, gave evidence that the number of quark species is really three times what was previously thought, consistent with the colour hypothesis. However, at this time there was no evidence which would compel one to accept quarks, “colourful” or otherwise, as genuine physical entities. All attempts to observe spin $\frac{1}{2}$ particles with fractional electromagnetic charges had failed. Thus, for a large class of physicists, the quark hypothesis was just a kind of “mathematics” that explained very neatly a whole lot of observed properties but did not require quarks to actually exist.

In the meanwhile, indirect evidence for both the quark hypothesis as well as the colour hypothesis was mounting, in different experiments such as muon-antimuon pair production in pion-proton collisions, or the production of strongly interacting particles in electron-positron collisions.

One of the obvious things to do, as per the list given in the earlier section, was then to perform scattering experiments to see if indeed p has a spatial extension to begin with. One could think later of addressing the question whether the scattering could reveal existence of these funny objects postulated from the requirements of patterns. As mentioned above, results of the various high energy experiments had agreed with the prediction of the “quark” model any way. So in that sense the third item on the “to do” list of the earlier section had been taken care of.

Similar to the experiments with the Nuclear targets, Hofstadter actually confirmed that indeed the p/n were charge distributions and the radius of this distribution was

100,000 times smaller than one Angstrom : it was ~ 1 Fermi. One thing to note here is that when we consider the scattering process,

$$e(E_e) + p \rightarrow e(E'_e) + p \quad (2)$$

e scattered at a given angle θ for a given energy of the incoming electron E_e will have to have a given value of energy E'_e , (say E'_0). The real surprise came as the energy of the electron was further increased to 10,000 – 20,000 million electron volts, reducing thereby the distance it could probe hundredfold compared to the size of the p/n . The scattered electrons at a given angle came with all possible energies, indicating thereby that may be the p had something inside it. In principle using the angle at which the electron travels and its energy, one can back calculate the momentum carried by whatever might be making up the proton. Thus the observed distribution in the energies of the scattered electron at a given angle then can thus be transformed into a distribution in momenta carried by these ‘constituents’. The most interesting observation was that this distribution was the same when obtained using electrons of different incident energies and scattered at different angles. Thus indeed, the assumptions in the back calculations were correct and the electrons were bouncing off something else inside the proton. Thus not only we knew that the proton had some more things inside but we can also map the distribution of the momentum of the proton that these constituents carried. The results indicated that by now the wavelength of the probe was small enough to feel the effect of the individual scatterers inside the proton, separately.

Needless to say I have oversimplified this second coming of quarks. It suffices to say that the measurements of the above mentioned distribution in the energy of the scattered electrons, for a few different values of the scattering angles, allowed the physicists to even get information about the possible spin as well as the electric charge of these elementary constituents. It was indeed gratifying to see that these constituents seemed to have all the properties (along with “colour”) which they were required to have in the Quark Model. Thus one could identify these observed constituents of the p with the quarks postulated by Gell-Mann and Zweig.

As a matter of fact, results obtained by scattering higher and higher energy e off the protons, indicated that the proton contains some other point like constituents to which the electron beam is blind, as they do not carry any electromagnetic charge. This was the first experimental glimpse of gluons. Actually these scattering experiments, the so called Deep Inelastic Scattering experiments, yielded very useful pointers which allowed physicists to formulate the right mathematical theory describing interactions of these quarks with each other and gluons. The Nobel Prize for Physics for the year 2004 was actually awarded for that theory called Quantum Chromo Dynamics (QCD). But that can be a topic of a separate article. The one feature of this theory that has implications for the present discussion is that, with increasing energy the number of constituents goes on increasing, since more and more quarks and gluons are created inside the proton, when one tries to probe it with higher and higher energy. **That is, the increasing energies do not reveal any new constituents but reveal only this increasing number of quarks and gluons inside. This is in fact a firm prediction of QCD.** In the simplified picture that I mentioned above, the peak in the scattered energy electron distribution will keep on shifting to values indicating an increasing number of constituents in the proton. Indeed such a rise was observed, precisely in the

manner predicted by QCD, thus proving that electrons and quarks are indeed point like and QCD the right framework to describe the dynamics of interactions among quarks and gluons!

A reasonable question to ask is whether the existence of constituents inside a nucleus could also have been inferred from similar experiments with nuclear targets, in case we had not known about them before. The answer is yes. Such experiments were indeed performed and the results did indicate existence of point-like scattering centers inside the nucleus just as in the case of the proton and even the number of nucleons could be deduced. The only thing is that the distance scale and hence the energies of incoming e beams for which it was observed are scaled appropriately.

At present experiments have been performed, not just with e beams, but also μ beams and ν beams, with energies about 10-50 times higher than the above. In an experiment in Germany, 30,000 MeV electrons are collided against protons which have an energy of 920,000 MeV. This corresponds to using an electron beam with an energy of 100 Billion (1 Billion is one thousand million) electron volts in the simple scattering experiment we have talked about. None of these experiments revealed any deviations from the expectations of the theory of point-like quarks and gluons, i.e., the above mentioned QCD. Thus there is no indication of any substructure of a quark up to a 1000^{th} Fermi. Thus we believe we have reached the end of the road in substructures.

So are we saying this simply because we don't have high enough energy probes? Indeed not. This is where the part about the Particle Physics, the dynamics, which I have left out comes into play with full strength. Recall that this scattering (or equivalently "seeing") of the constituents was only *one* way in which we hunted for what lies at the heart of the matter. At present every single piece of experimental observation agrees to a very high accuracy, better than to one part in a 100 Millions at times, with the predictions of a theory which in these calculations, treats these quarks and leptons as point-like up to energies ~ 10 billion billion eV. Thus we have an "indirect" *but very strong* proof that the quarks and the leptons are indeed point-like and have no further substructure.

It should be added that I have sketched the path how we have arrived at the idea of quarks, in great detail and not said much about leptons. In fact they were not hunted for, but just came uninvited and made their appearance in the cosmic ray as well as in the high energy experiments. Their properties never gave any indication of substructure, the results of scattering reactions in which only leptons were involved always agreed completely with predictions made assuming that they were point-like. While, theory can not tell how many different repetitions of these pairs of quarks and leptons should be there, what the theory IS able to tell is that these should be equal in number. Indeed, this is satisfied by the current list of the fundamental constituents of matter. I have also not discussed how the force carriers were "discovered". But that requires a much more detailed discussion of dynamics of the particle interactions, which we have left out.

Thus the discussion now clearly shows that the notion of what is elementary is really decided by the resolving power of our probes, hence the distance scales we are interested in. All the discussion in these earlier sections can be summarised as shown in Fig. 7. The figure shows the constituents of matter as we see them at different distance (and hence energy) scales.

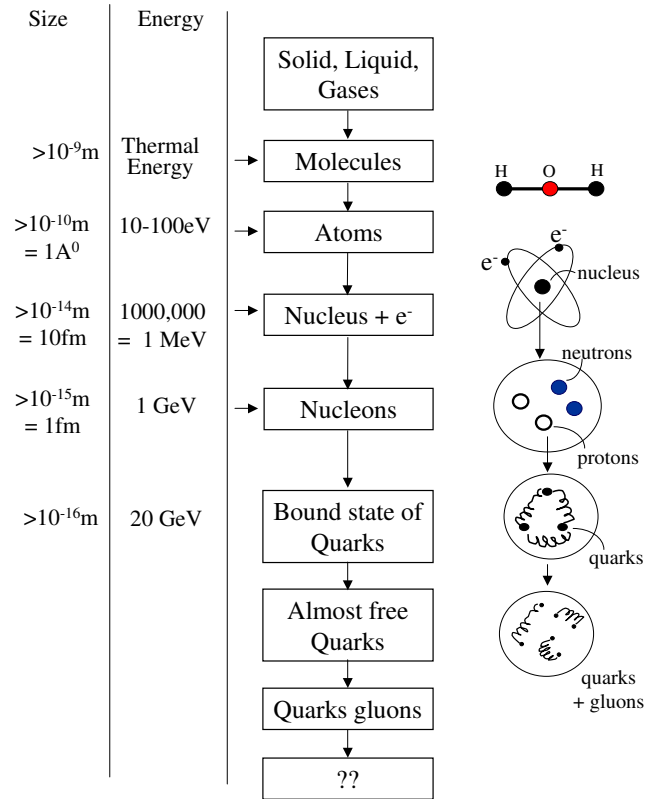


Figure 7. *Constituents of matter at different distance and energy scales*

Recall here also Fig. 4. This figure tells us that high energy accelerators are our microscopes as we probe distance scales of atoms/nuclei and further. Thus this journey into the 'Heart of Matter' is accompanied by the development of accelerators. Figure 8 shows the way the energy frontier has moved through the decades and the distance scale of the new physics that this higher energy has revealed. Through the early part of this journey the higher and higher energy just revealed constituents at smaller and smaller distance scales. After the discovery of the quarks lying at the heart of protons and neutrons, the later increase in energy has brought about production of the force carriers and helped develop/test the theory which can describe the interactions among the fundamental constituents. The Large Hadron Collider (LHC) that has just gone into operation at CERN in March 2010 and the International Linear Collider (ILC) or CLIC that are under planning are the spearheads of this energy frontier. We will discuss these next and present what we expect them to achieve.

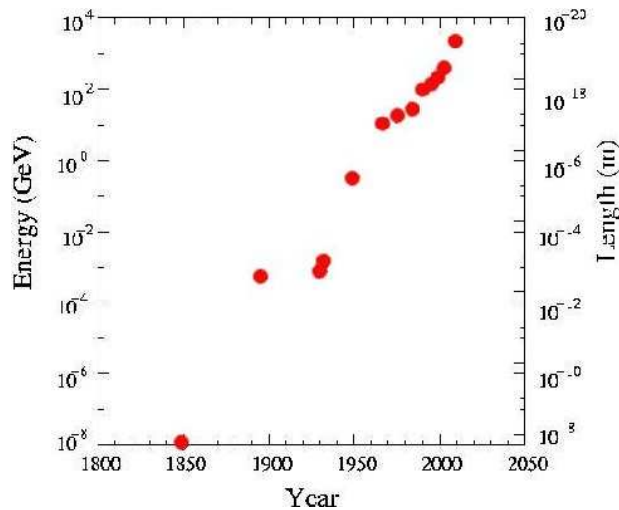


Figure 8. *How the energy frontier has moved in the decades.*

6. What Next?

Following all the discussions in the earlier sections, one might be tempted to ask, now that particle physicists seem to believe that they have arrived at a description of the ultimate constituents of matter and the interactions among them, does it mean that this is the end of the road for the subject? Not at all. There are various reasons which tell us that we still have quite a way to go.

- 1 Firstly, the Higgs Boson which is predicted by these theories has to be found and shown to have exactly the properties that the theorists predict it must have. This is almost like checking that the constituents of the p as seen in the scattering experiments were indeed the quarks of the Quark Model.
- 2 Even if these experiments were to find this Higgs Boson there are still a lot of issues that need to be addressed and handled. Even in the case of the Standard Model itself, there are theoretical challenges such as understanding how massless quarks, anti-quarks and gluons make bound states that are massive, why free quarks never appear in nature etc. There are certain unsatisfactory theoretical issues about the high energy behavior of the dynamical theories involving Higgs Bosons. Efforts to cure these problems have led to some popular extensions beyond the SM. These predict existence of particles beyond what we have seen.
- 3 The ν 's have zero mass in the SM. However, the recent Nobel Prize winning experiments which showed that ν of one type can change into a ν of another type, have now firmly established that these have a non-zero mass. Thus there are indications that the dynamics has something more than the SM.

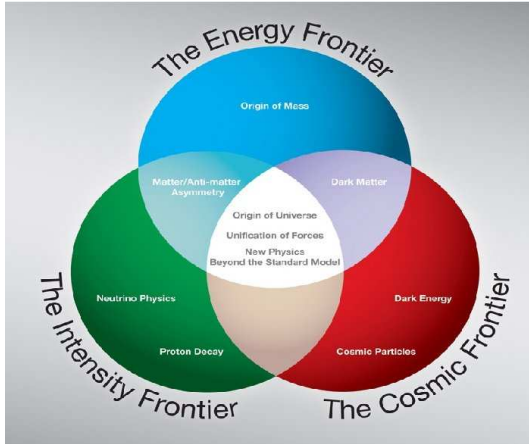


Figure 9. *The three frontiers of progress in Particle Physics*

- 4 Further, even the three interactions that the SM addresses are not truly unified. Particle physicists, including Einstein, have always held the dream of such a unified description, one encompassing even gravity. So theorists are exploring ways to go beyond the dynamics contained in the SM.
- 5 In the heavy ion mode of the LHC the collisions can recreate energy densities and temperatures which existed in the early Universe, giving us a chance to actually study the transition of the ordinary matter into a Quark Gluon Plasma which again metamorphoses into hadrons. This part in the evolution of the early Universe is opaque to various cosmological measurements and the LHC is our only chance to study this in laboratory condition.

To summarise the above, we certainly need high energy accelerators which can give us direct evidence for the Higgs boson. In addition, various extensions of the SM also make predictions of existence of new elementary particles and/or processes. The non-zero mass of the ν s is indeed an extremely strong indicator for the existence of Physics beyond the SM. Studies of the ν sector may therefore provide us with theoretical and experimental clues to the Physics beyond the SM.

It is obvious from the above discussions that the future of particle physics rests on explorations on different fronts: a) theoretical investigations to address various issues mentioned above and b) different experiments where these can be tested viz. These are i) experiments at high energy accelerators ii) experiments with high energy neutrinos and iii) the cosmological connections. In fact this state of affairs has been depicted very succinctly in Fig. 9, taken from the report of the High Energy Physics and Astrophysics Panel (HEPAP), of the National Academy of Sciences, USA. The confluence of the results obtained at different frontiers will lead to fundamental progress in our knowledge of the Universe. Indian Scientists are in fact involved in activities on all the fronts.

On the energy frontier there is the Large Hadron Collider (LHC) which has gone into action in March 2010, albeit with lower energy than was initially foreseen; perhaps these teething problems remind us of the complexity of the machine. The LHC is a proton-proton collider, where the two beams of protons circulate in opposite directions in two beam pipes which run inside a tunnel with periphery 27 km long. These two pipes intersect at a few chosen points so that the beams can collide. The beam bunches have to maintain their micrometer size diameter while traveling the distance of 27 km, which they traverse thousands of time. To achieve collisions of the required number of high energy protons, the beams have to be steered by superconducting magnets which are kept at a temperature of 1.9° K. Building such complex piece of machinery and making it work has been a matter of great joy and pride to the international high energy physics community. We can be very proud that Indian engineers and accelerator physicists have been involved in building some part of this machine. The so called Precision Magnet Positioning Systems (PMPS) were manufactured in India. Not just this, Indian physicists have also been involved in building the mammoth detectors which are capable of making very precise measurements (such as determining the position of a particle within a micrometer!) and thus can probe the mysteries of the laws of nature at their deepest level. India participates in the general purpose pp detector CMS as well as the ALICE detector which will study the heavy ion collisions. Figs. 10



Figure 10. *The LHC tunnel with its accelerating magnets.*

and 11, show the LHC tunnel with the accelerating magnets and the cut out view of the CMS (Compact Muon Solenoid) detector to which India has contributed. Thus the Indian scientific community is a part of this adventure. Indian theorists are involved in the development of new and/or more refined theories of the Physics beyond the SM as well. Indian physicists will also be involved in interpreting what the results coming out of LHC would mean for the SM and for the various theoretical ideas which go beyond the SM.



Figure 11. *The CMS detector in which India participates.*

The international high energy physics community is convinced that it is necessary to have an e^+e^- collider, which should go in operation after LHC has run for a few years. This is truly an international effort in that even the optimal parameters for such a collider were decided by the entire international community. The same pattern continued in deciding the optimal accelerator technology and now finally even the design of this accelerator is being done by an international team. Indian groups are part of this global exercise as well and there exists an Indian Linear Collider Working Group (ILCWG). A schematic drawing of the radio frequency cavities that would have to be built, in order to construct the ILC is shown in Fig. 12. In fact the future consists not just of these collider experiments but also the gigantic Neutrino Experiments and India is part of that as well. Indian High Energy Physicists are planning to build the Indian (International) Neutrino Observatory (INO). A prototype of the iron calorimeter they plan to use is shown in Fig. 13. You can get more information on the ILC, INO etc. from the websites: <http://cts.iisc.ernet.in/Meetings/LCWG/index.html>, <http://www.linearcollider.org/> and <http://imsc.res.in/ino/>.

Actually, there is one more important laboratory where particle physicists can apply/test their theories and that is the Cosmos ! Cosmological observations now have reached a degree of precision rivaling that of the HEP measurements. Measurements by the Hubble telescope, the Sloan Digital Sky Survey, the Wilkinson Microwave Anisotropy Probe etc., have now essentially tested the Standard Model of Big Bang Cosmology to a great degree and gone beyond it. Very high temperatures are supposed to have existed in the early Universe and at those temperatures all the fundamental particles would have existed. Their properties affect the evolution of the Universe in its first three minutes. The number of mass less neutrino species, for example, affects what the value of the abundance of different type of elements in the Universe should be. Thus a knowledge of the spectrum of fundamental particles and their interactions is indispensable in the study of Cosmology. In the reverse, some of the ideas of physics



Figure 12. Schematic drawing of a Radio Frequency cavity for the future International Linear Collider.

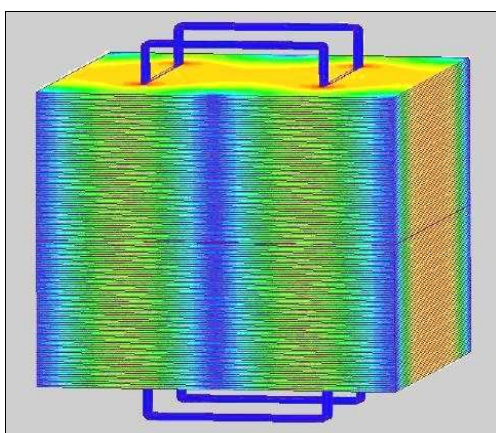


Figure 13. Prototype of the INO iron calorimeter

beyond the SM can also be tested by their implication for cosmology. This interplay between High Energy Physics and Cosmology is most exciting.

For example, it is now well established that indeed the Universe consists of matter which does not shine, the so called Dark Matter (DM), whose presence is revealed by its gravitational effects. At one stage ν 's used to be a favorite DM candidate. However, very accurate measurements of the Microwave Background Radiation put now an upper limit on how much the ν 's can contribute to the DM. One of the most promising ideas of going beyond the SM called Supersymmetry, necessarily predicts existence of a particle with exactly those properties that the cosmological calculations of fluctua-

tions in the Microwave Background Radiation need. This particle called the lightest supersymmetric particle (LSP) will be hunted for at the accelerators as well as in the Astrophysical experiments.

Further, it is found that matter dominates over the anti-matter in overwhelming proportions in the Universe, this is basically the reason why we exist. In particular, the relative number density of p/n (more generally baryon) with that of the γ 's is about 10 million times larger than the same for \bar{p}/\bar{n} . This dominance can be understood in the Big Bang Model if 1) there existed interactions which did not conserve the proton number and 2) further violated the symmetry associated with the combined transformation of charge conjugation (which exchanged particle and antiparticle) (C) and space reflection (P), viz., CP. Indeed, the grand-unified theories have ready-made candidates for interactions that violate the proton number. The quarks themselves do violate the CP symmetry by a very small amount. The quantitative calculation of this baryon asymmetry again seems to indicate that this observed and known CP violation present in the quark sector may not be quite enough, thereby indicating a possible class of models for going beyond the SM. Again, these models can be readily tested at the current and future colliders. Alternatively, same mechanism that gives masses to the ν 's can also give rise to adequate baryon asymmetry. This too can be tested in the accelerator experiments. Thus the Cosmology firstly provides strong constraints on the Particle Physics Models and secondly indicates regions of parameter space for these models where a satisfactory Baryon asymmetry can be obtained and thus makes the accelerator search for them more focused. This interplay between Cosmology and Particle Physics is truly fascinating.

The latest in the line is the so called Dark Energy. It seems to be proved that our Universe is slowly accelerating. This, along with the precision measurements of the Hubble constant and hence the age of the Universe, essentially imply that a large amount of Vacuum energy is present in the Universe. The answer to this issue may be linked with how we unify gravity with all the other interactions, what is the Quantum theory of Gravity etc. Since these are precisely the kind of issues that String Theorists are worrying about, it is likely that the latest Cosmological puzzle may find its solution in Particle Theory and Particle Theory may get hints about physics at the heart of matter through this. Again, only time can tell. But it is clear that our knowledge about the fundamental particles and their interactions can now address Cosmological issues. We in turn may get pointers for our searches of new physics and towards our theories of the very fabric of Space and Time, from these Cosmological observations. So great things are in store.

Acknowledgments

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